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FATIGUE LIFE ASSESSMENT OF 155-MM M284 CANNON TUBES

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13. ABSTRACT *(Maximum 200 words)*

Benet Laboratories has the responsibility for safe service life (fatigue) testing of cannon system components. This safe service life evaluation is accomplished by conducting constant amplitude fatigue tests using hydraulic oil as the pressurized medium. One such cannon component that requires testing is the gun tube. After each tube has received the required number of live fire rounds necessary to generate heat check cracking in the bore, it is brought to the laboratory for final hydraulic fatigue testing.

A sample size of seven 155-mm M284 gun tubes was hydraulically fatigue tested to failure at Benet Laboratories to determine the safe service life for the weapon. This report contains the results of the fatigue tests conducted on the subject tubes, including material inspections, failure lives, and the resulting safe service life.

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INTRODUCTION

Benet Laboratories has the responsibility for safe service life (fatigue) testing of cannon system components. This safe service life evaluation is accomplished by conducting constant amplitude fatigue tests using hydraulic oil as the pressurized medium. One such cannon component that requires testing is the gun tube. After each tube has received the required number of live fire rounds necessary to generate heat check cracking and crack initiation sites in the bore, it is brought to the laboratory for final hydraulic fatigue testing.

A sample size of seven 155-mm tubes, consisting of both prototype (XM284) and production (M284) tubes, was hydraulically fatigue tested to failure at Benet Laboratories to determine the safe service life for the tube. The subject tubes are serial numbers (SN) 1, 2, 3, 5, 9, 11, and 825. The first 57 inches of each tube, measured from the breech end, was cyclically pressurized to 57,000 psi. This pressure, also known as the extreme service condition pressure (ref 1), represents the highest pressure developed in the chamber while firing the top zone charge under the most severe conditions for which the system is designed. Typically, additional tube sections forward of the breech section, from the first two tubes would also be tested to achieve fatigue lives of these various sections. Since this tube closely represents its predecessor, the 155-mm M185 tube, the testing of additional tube sections was waived.

The laboratory fatigue lives of the seven tubes ranged from 5,501 cycles to 13,800 cycles. Besides the cycles-to-failure data, additional data were gathered to characterize the tube material and nature of the failure. Mechanical and fracture properties were evaluated in the tubes adjacent to the fatigue specimen to validate material conformity. Prior to and during fatigue cycling, ultrasonic detection and other nondestructive inspection techniques were employed to detect and measure existing flaws, as well as the initiation and growth of fatigue cracks. Using the data gathered on the seven tubes, an engineering and statistical analysis was made to assess the safe service fatigue life of the tubes under the most severe conditions that they are expected to endure in actual use. This testing has met all conditions of the International Test Operations Procedure (ITOP) (ref 1) as required by the Test and Evaluation Command (TECOM), Aberdeen Proving Ground, Aberdeen, MD.

TEST SPECIMEN DESCRIPTION

The seven tubes were manufactured by Watervliet Arsenal between 1982 and 1990. These tubes were sent to various sites for test firing and returned to Benet Laboratories for hydraulic fatigue testing. The loading history for each tube is listed in Table 1. Upon arrival at Benet, a number of test samples were taken from the tubes to verify if enough live fire rounds had been applied. A minimum number of live fire rounds are necessary to generate heat check damage at the bore surface. This is essential for laboratory cycling to be effective for the accurate determination of safe service life. It is typically from these small heat checks that inside diameter failures originate. Figure 1 illustrates a macroscopic view of the bore surface of Tube SN3 after live fire rounds had been applied but before laboratory cycling. The heat checking, or "dry lake bed" appearance, is apparent. Figure 2 is a transverse section of Figure 1 showing the uniform array of heat checks and the fatigue cracks that grow from heat checks. The heat checking in this photograph ranges from 0.010 inch to 0.020 inch. Figure 3 is a high magnification micrograph of Figure 2. Once again, a fatigue crack emanating from a heat check location is apparent. Finally, Figure 4 shows how a heat check crack has initiated a fatigue crack that has penetrated through the chromium plate and into the base metal.

As stated earlier, the first 57 inches of each tube, as measured from the rear face, was removed from each gun tube to form seven identical laboratory fatigue specimens. The configuration of these specimens included two unique geometry shapes, i.e., the internal charge notch and the external torque keyway. As with the predecessor to the M284, the M185, fatigue failures from the outside diameter of the tube initiated at the torque keyway, while inside diameter failures initiated at the charge notch. It should be noted that the heat checks described above are contributory to failures originating at the bore only. Failures originating from the outside surface of the tube obviously cannot be traced to heat checking. The configuration of the test specimen is illustrated in Figure 5. Figure 5 also shows the locations of mechanical property discs used to characterize the material of each tube.

Once the specimen was cut to length, sealing pockets were machined into each end of the specimen. It was in these pockets that the seals and closures fit to provide the required sealing during the test.

TEST PROCEDURE AND EQUIPMENT

Historically, two methods of sealing closure support can be used during the fatigue testing of cannon tubes, the mandrel support method or the load-frame support method. The subject tests were conducted using the mandrel support method. This approach used a large maraging steel mandrel that was passed through the center of the test sample. Each end of the mandrel was threaded to accept large nuts, which kept the sealing closures in the seal pockets during testing. This method is illustrated in Figure 6. High pressure fluid was pumped through a small, angled porthole in the mandrel. The fluid entered the test specimen from the mandrel at a point between the two sealing closures. With this scheme, the only end loads reacted by the mandrel were those generated by pressure acting on the annular ring of the sealing area between the mandrel and the test specimen. A photograph of the entire test setup is shown in Figure 7.

The seals consisted of a rubber O-ring, a neoprene back-up ring, and an aluminum wedge ring in each sealing pocket. The rubber O-ring served as the low pressure seal and, as the pressure rose, forced the wedge ring against the sealing pocket of the tube. The combination of a well-machined sealing pocket and a snug fitting wedge ring did not allow the rubber O-ring to extrude past the sealing closure, thus producing an acceptable seal.

The pressurized fluid medium was generated by a pressure intensifier and plumbed to the test specimen. The intensifier is a hydraulic cylinder with an upper and lower piston head. The 15-inch diameter lower piston is acted upon by standard hydraulic oil pressurized to 3,000 psi. The reduction to the smaller 2.25-inch diameter upper piston causes an increase in pressure based on the ratio of areas. With respect to fluid compressibility and specimen volume, pressures as high as 100,000 psi can be obtained. The intensifier is able to displace approximately 40 cubic inches per stroke. The fluid used during this test was a low viscosity synthetic oil capable of sustaining pressure of approximately 135,000 psi without solidifying. Pressure was monitored by a Heise gauge with an accuracy of ±0.5 percent at 100 Ksi. Pressure was controlled by a bulk modulus operated automatic controller. An in-line pressure transducer feeding a data acquisition station was also used to monitor and record each pressure cycle. A specimen-mounted strain gauge was also in place to record strain throughout the test, thus four pressure monitors were in operation continually during cycling.

Inspections were conducted prior to and during testing by employing nondestructive testing techniques to measure crack growth as well as material defects and flaws. Cracks growing from the bore were measured by ultrasonic inspection. This was carried out by a level II certified inspector using Krautkramer USIP-11 flaw detectors and 5 to 15 MHz probes. Cracks growing from the outside surface of the tube were identified using magnetic particle inspection.

Upon failure each specimen was cut, split, and photographed to reveal the fatigue fracture surface.

RESULTS

Results from the seven-sample fatigue test are listed in Table 2. Results from the material property tests are listed in Tables 3 through 7. Figures 8 through 21 show the failure location and the fracture surface for each of the seven test samples.

As Table 2 demonstrates, four of the test samples failed in the torque keyway, while the remaining three samples failed in the charge notch region. Tube SNs 1, 5, 9, and 11 failed in the torque keyway. All of these tubes experienced uncontrolled, running cracks at the time of failure, as has been observed with 155-mm M185 tubes. Of the charge notch failures, Tube SNs 2 and 3 failed in a ductile mode with steady crack growth, while Tube SN825 experienced an unexpected running crack emanating from the charge notch and continuing to the breech face of the tube. There was no material fragmentation associated with any of the seven failures. Figure 22 illustrates the fatigue crack growth rate for the three tubes that failed from cracks emanating from the bore. All three curves show a similar critical crack depth, though Tube SN825 reached that crack depth much sooner than did Tube SNs 2 and 3.

It is noteworthy to mention that the -40°F Charpy impact energy and the fracture toughness values for Tube SN825 are lower than any other tube that failed in the charge notch. These two values do not correlate with any accuracy to the upper-shelf correlation of Barsom and Rolfe (ref 2), since this correlation is based on different types of steel. These low Charpy and fracture toughness values are considered to be the cause for the unstable (running crack) mode of failure of Tube SN825.

SAFE SERVICE LIFE FATIGUE ANALYSIS

As allowed by the ITOP, the mechanical safe service life (as opposed to wear life) for the 155-mm M284 cannon was computed using the two-parameter lognormal distribution method (ref 3). Statistical procedures for the lognormal distribution are derived from procedures for the normal distribution. In particular, if we have laboratory fatigue failures $x_1, ..., x_N$, then the mean and the standard deviation of the logarithms are calculated as follows:

$$y_i = \ln x_i \text{ for } i = 1, ..., N$$
$$\text{mean, } m = (1 / N) \times (y_1 + ... + y_N)$$
$$\text{standard deviation, } s = [\, (1 / N - 1) \times [(y_1 - m)^2 + ... + (y_N - m)^2 \,] \,]^{1/2}$$

With the mean and the standard deviation of the logarithms known, the mechanical safe service life can be calculated using the following formula:

$$\text{mechanical safe service life} = \exp [\, m - Ks \,] \;;$$

where K is a tolerance factor (ref 3) dependent only on confidence, reliability, and sample size. Benet Laboratories uses tolerance factors based on 90 percent confidence and 0.999 reliability. Based on our sample size of seven tubes, the tolerance factor of 5.201 produces an estimated mechanical safe service life of 2,003 rounds.

It should be noted that the projected sample size when testing began in 1985 was six samples, the minimum required by the ITOP. As a result of the apparent premature failure of the sixth test sample, Tube SN11, after only 5,501 lab cycles, a seventh tube was included in the test. An investigation into the causes of the failure of Tube SN11 was completed, and the results of that investigation are listed in Reference 4. As a result of that investigation, a full field survey is being conducted to determine if any other tubes exhibit properties similar to those exhibited by Tube SN11. The intent of that survey is to locate, repair, and/or purge the inventory of any such tubes. Once this is accomplished and validated with accuracy, only then can Tube SN11 be removed from the mechanical safe service life analysis yielding a tolerance factor of 5.556 and an estimated mechanical safe service life of 4,246 rounds. Until the survey and repair procedure have been completed and verified, the estimated mechanical safe service life shall be based on the population of all seven samples.

REFERENCES

1. "International Test Operations Procedure for the Cannon Safety Test," ITOP Report #3-2-829, U.S. Army Test and Evaluation Command, Aberdeen Proving Ground, MD, 1992, p. 4.

2. Barsom, J. M., and Rolfe, S. T., "Correlations Between K_{Ic} and Charpy V-Notch Test Results in the Transition-Temperature Range," *Impact Testing of Metals, ASTM STP 466*, American Society for Testing and Materials, Philadelphia, PA, 1970, pp. 281-302.

3. "International Test Operations Procedure for the Cannon Safety Test," ITOP Report #3-2-829, U.S. Army Test and Evaluation Command, Aberdeen Proving Ground, MD, 1992, p. C-3.

4. Audino, M., Underwood, J., Troiano, E., Fujczak, R., Rickard, C., "Investigation of Early Failure During Laboratory Cycling of 155-mm XM284 Tube, Serial Number 11," ARDEC Technical Report ARCCB-TR-93025, Benet Laboratories, Watervliet, NY, June 1993.

Table 1. Pretest Loading Histories

Pressure (Ksi)	SN1	SN2	SN3	SN5	SN9	SN11	SN825
52.2	116	2	408	No	84	257	168
45.4	997	498	1,449	Gun	138	245	54
30.7	213	10	40	Record	845	1,923	1,551
25.1	288	11	84	Card	1,201	3,604	1,577
15.4	47	0	0	Found	381	888	1,741
Total Fired Rounds	1,661	521	1,981	1,291	2,649	6,917	5,091
Total Fired EFC*	1,332	504	1,857	N/A	625	2,799	980

* Effective full charge.

Table 2. Laboratory Fatigue Test Results

Pressure (Ksi)	SN1	SN2	SN3	SN5	SN9	SN11	SN825
57	13,800	10,319	13,067	10,828	11,252	5,501	8,501
Failure Location	Keyway	Charge Notch	Charge Notch	Keyway	Keyway	Keyway	Charge Notch

Table 3. Tensile Test Results

Tube SN	0.2% Yield Strength (Ksi)	0.1% Yield Strength (Ksi)	Ultimate Strength (Ksi)	Elongation (%)	Elastic Modulus (Mpsi)	Reduction in Area (%)
1	176.0	173.1	186.5	9.8	29.5	34.0
2	N/A	176.0	188.0	14.5	29.5	44.0
3	N/A	175.0	187.0	16.5	29.5	43.2
5	177.9	174.8	188.9	11.5	29.6	38.6
9	181.0	177.9	192.2	11.4	29.6	36.3
11	180.3	177.3	192.6	10.8	29.4	34.0
825	178.2	175.2	190.0	11.2	29.5	34.8

Table 4. Fracture Toughness Test Results

Tube SN	Fracture Toughness K_{Ic} (RT*)
1	122
2	172
3	138
5	137
9	123
11	103
825	119

* Room temperature.

Table 5. Charpy Energy Test Results

Tube SN	-40°F Charpy Energy* (ft-lbs)
1	22.3
2	24.0
3	24.0
5	24.7
9	22.3
11	22.0
825	15.0

* Mean value.

Table 6. Residual Stress Test Results

Tube SN	Expected Overstrain (%)	Actual Overstrain (%)
1	48 to 60	65
2		64
3		61
5		70
9		62
11		65
825		65

Table 7. Chemical Composition Test Results
(Weight Percent)

Element	SN1	SN2	SN3	SN5	SN9	SN11	SN825
Ni	2.28	2.36	2.34	2.23	2.33	2.12	2.09
Cr	0.97	0.91	0.90	0.99	0.95	0.91	0.95
Mo	0.43	0.42	0.43	0.42	0.43	0.41	0.49
V	0.14	0.13	0.10	0.12	0.13	0.11	0.09
Mn	0.52	0.51	0.51	0.56	0.61	0.53	0.66
Si	0.16	0.17	0.16	0.19	0.19	0.11	0.25
Cu	0.13	0.12	0.12	0.11	0.12	0.06	0.09
P	0.007	0.014	0.015	0.010	0.012	0.013	0.009
S	0.017	0.014	0.013	0.009	0.017	0.014	0.017
C	0.33	0.37	0.33	0.32	0.34	0.37	0.32

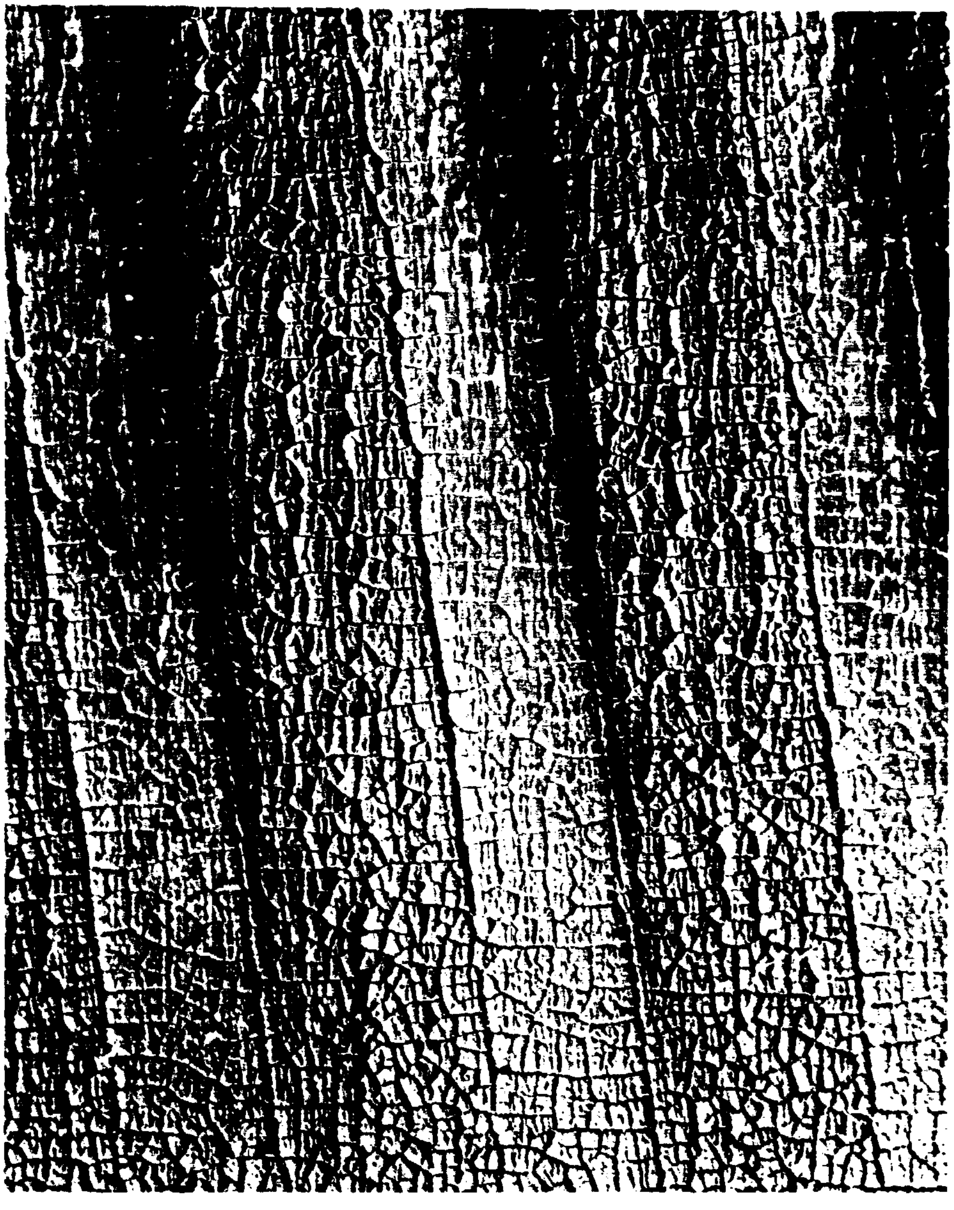

Figure 1. Micrograph showing heat checking in the origin-of-rifling region, 155-mm XM284 SN3, 15X.

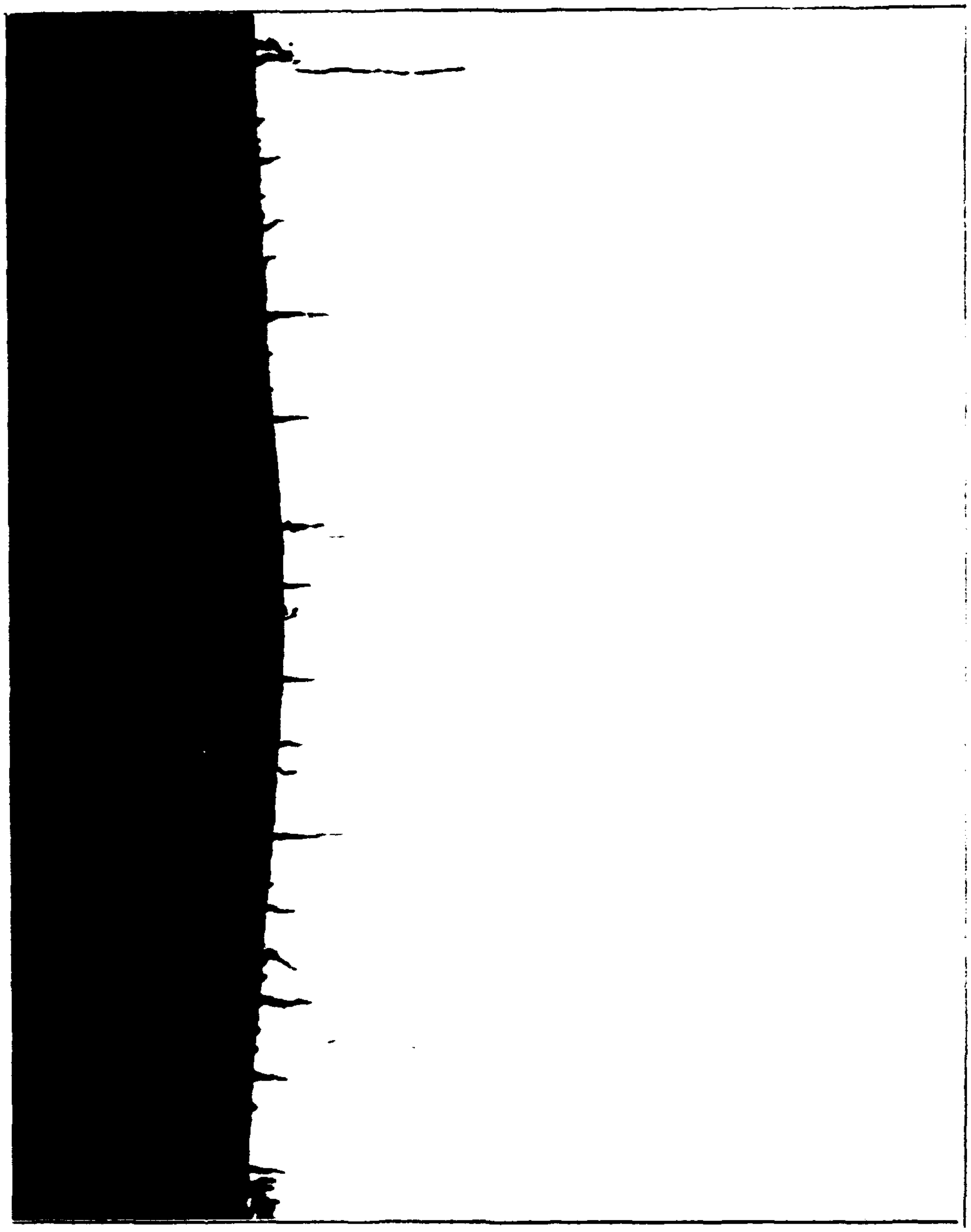

Figure 2. Transverse section of Figure 1 showing the uniform array of heat checks and fatigue cracks initiating from the heat checks, 15X.

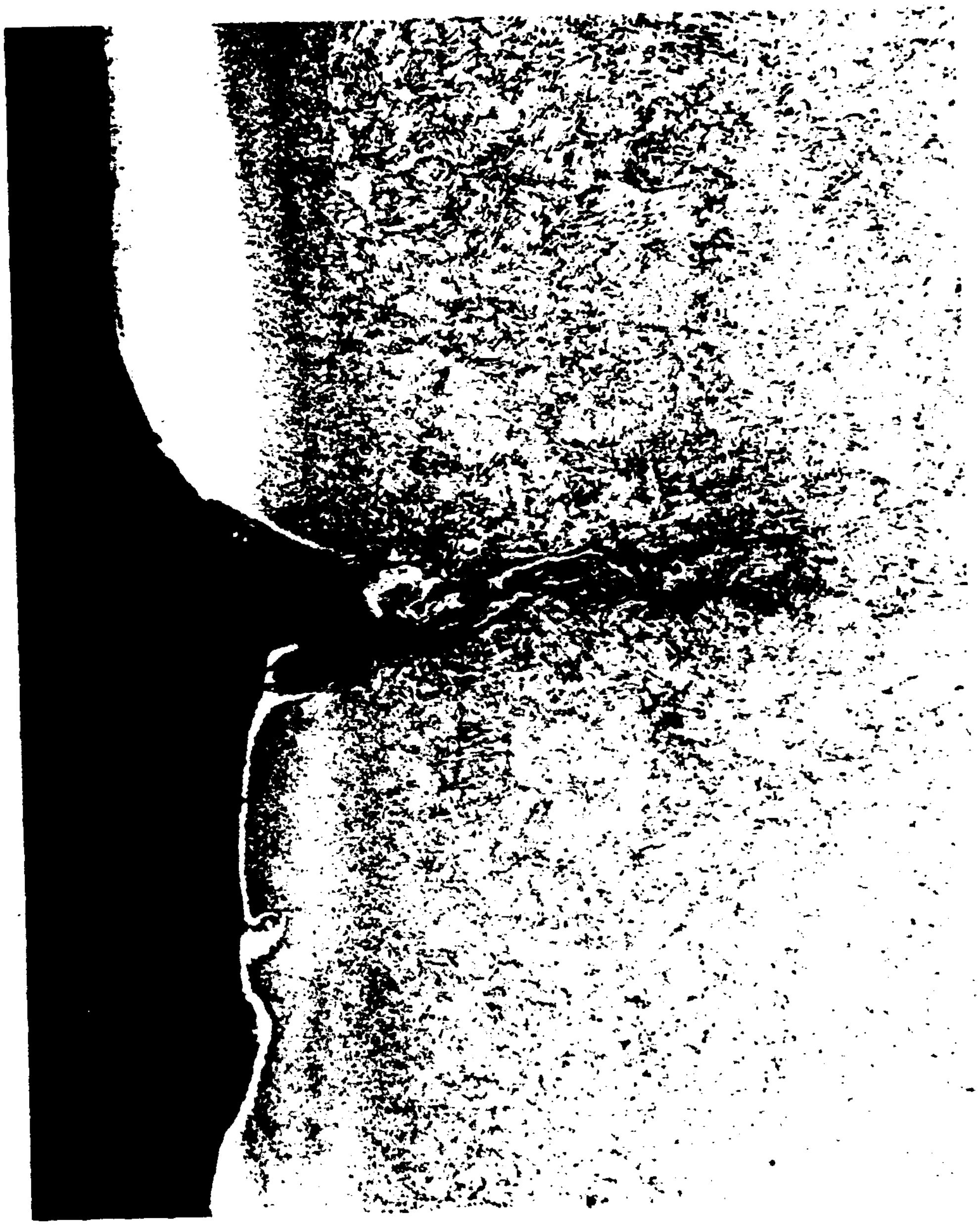

Figure 3. High magnification micrograph of the transverse section of a heat check showing the transition from a heat-induced crack to a fatigue-induced crack, 200X.

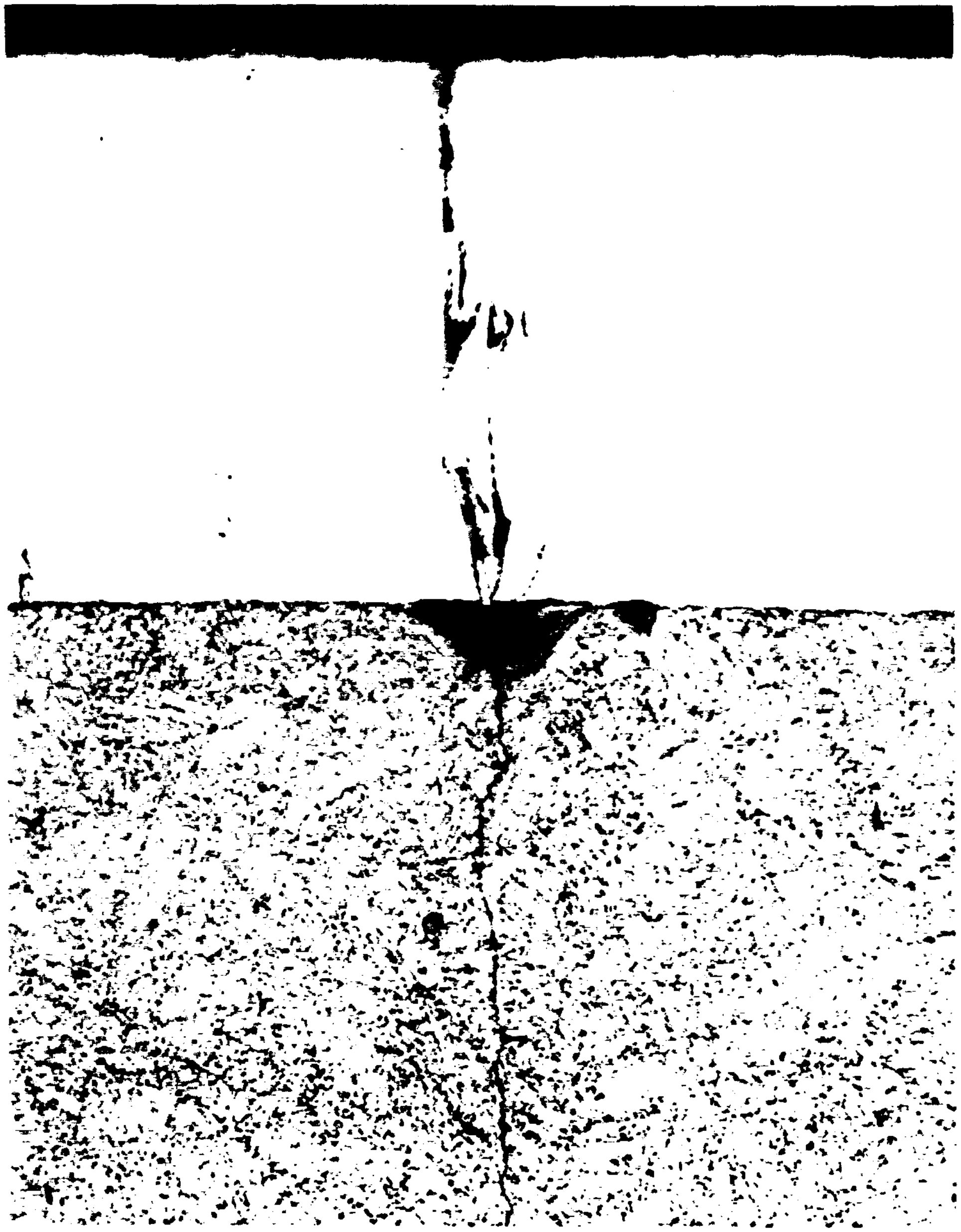

Figure 4. High magnification of Figure 3 showing penetration of the chromium plate that allows the propellant gases access to the substrate steel and the damage produced in the steel. Also shown are the fatigue cracks that initiate from contact between the steel and the propellant gases.

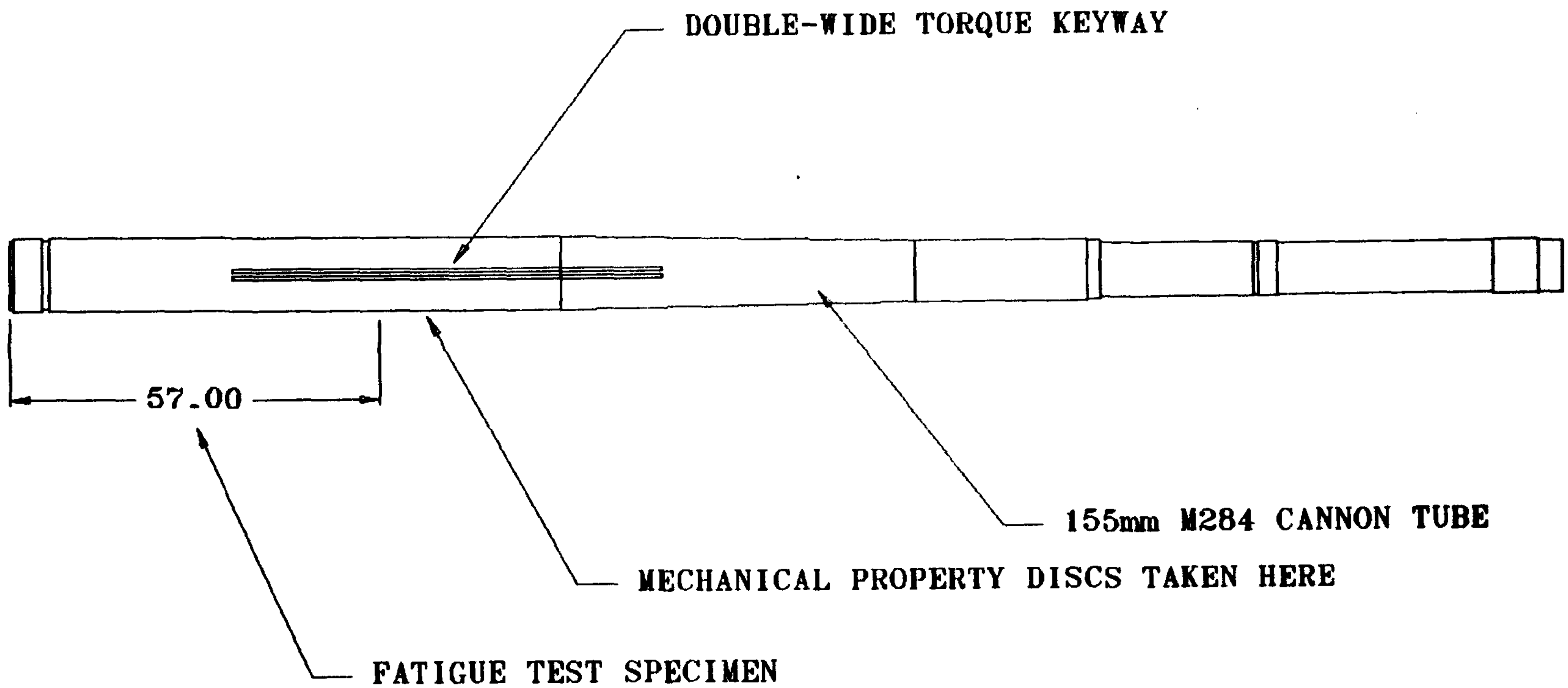

Figure 5. Tube cutting plan and specimen configuration.

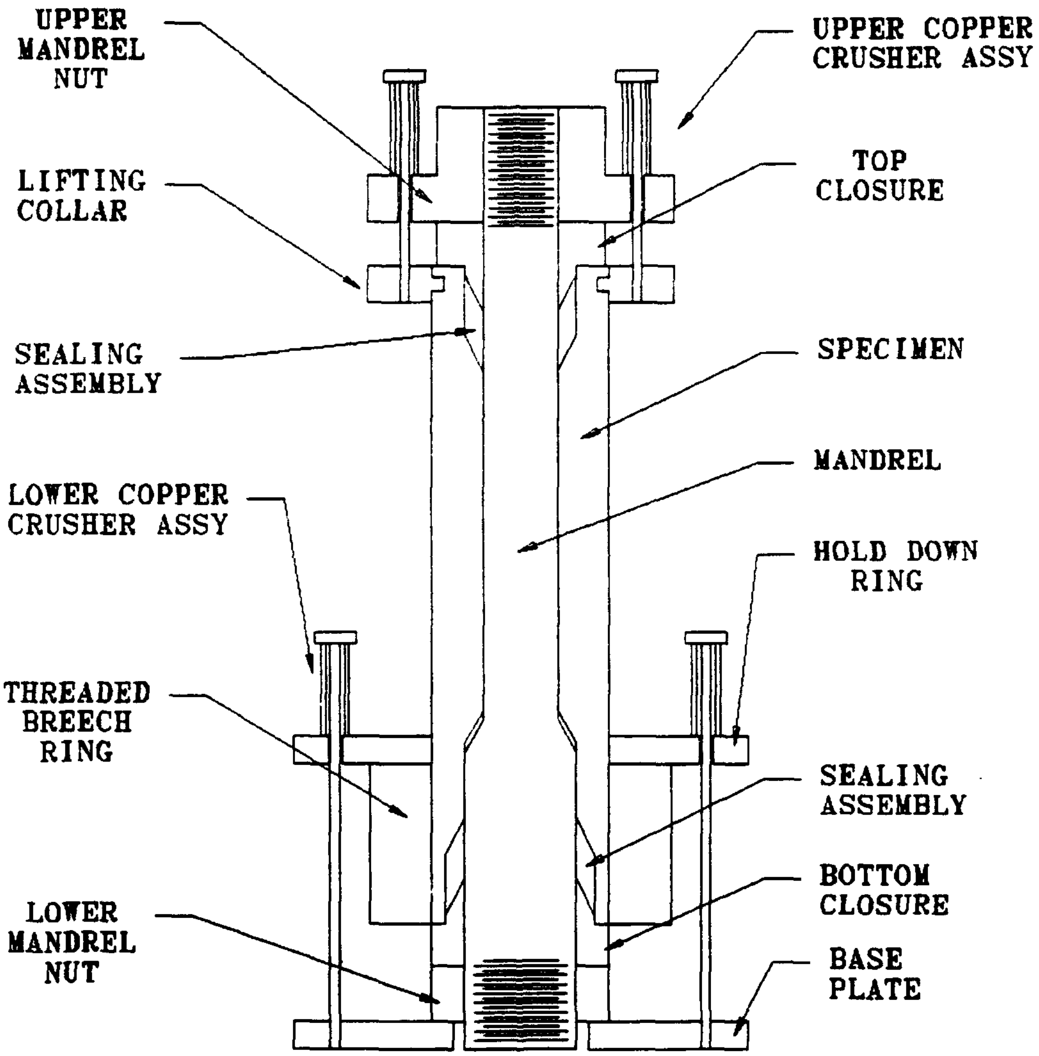

Figure 6. Mandrel support test method.

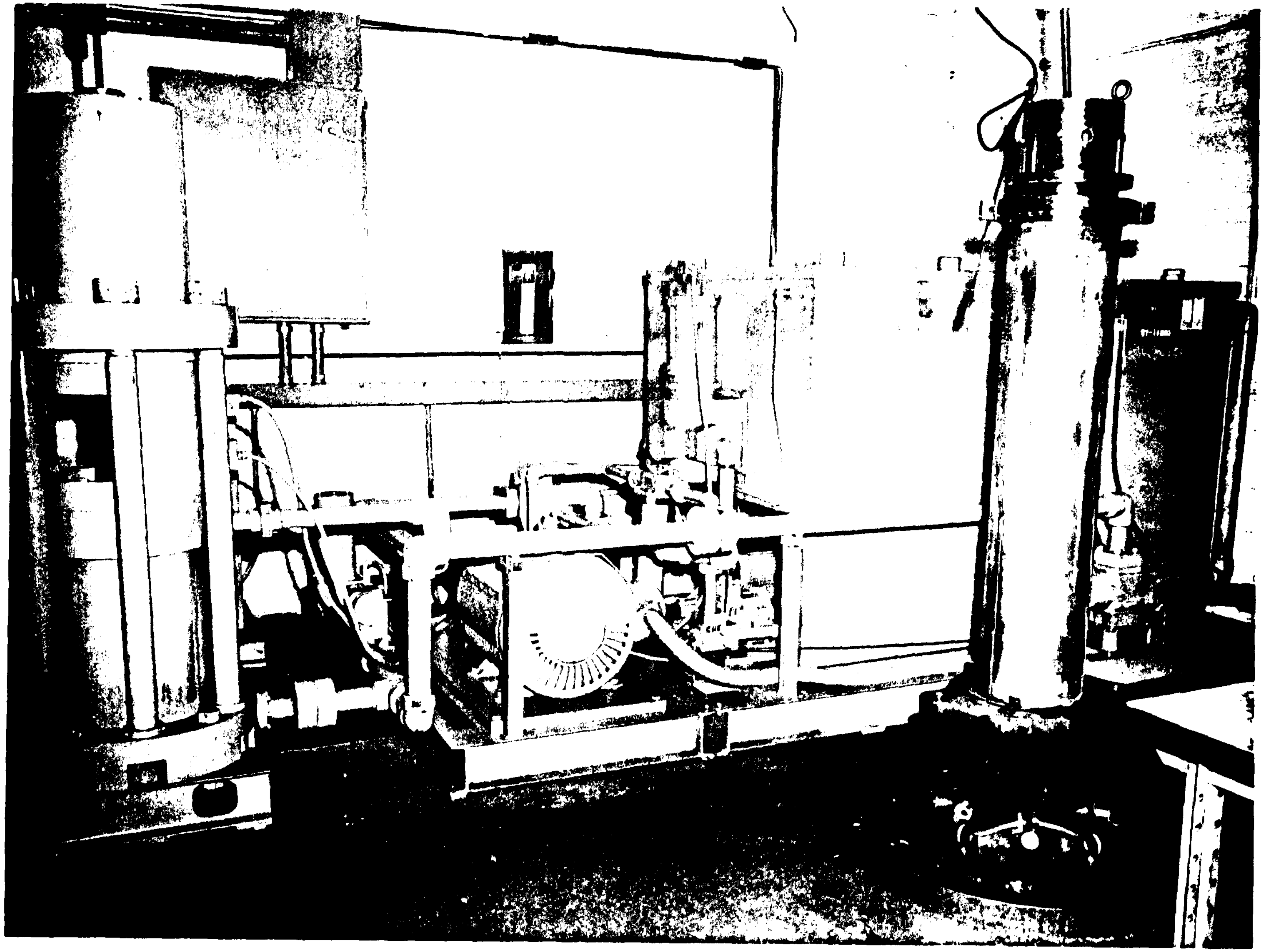

Figure 7. Test setup.

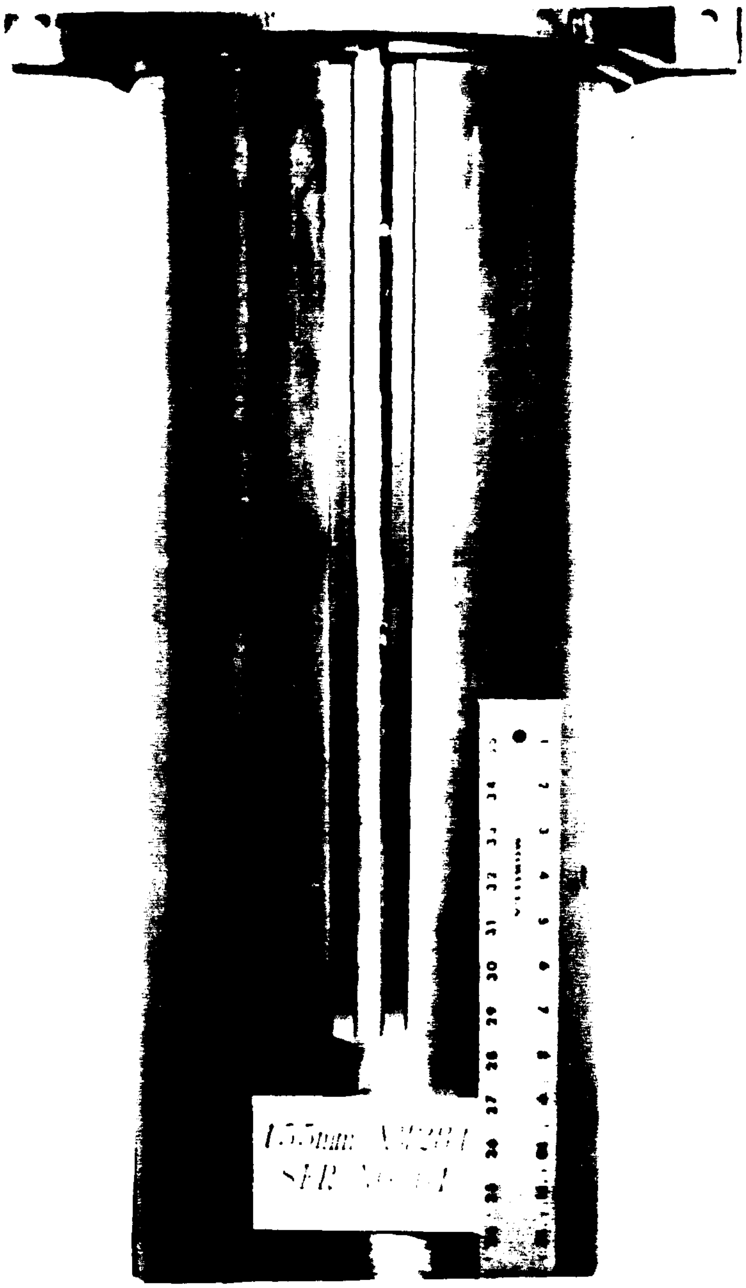

Figure 8. 155-mm XM284 Tube SN1 failure location.

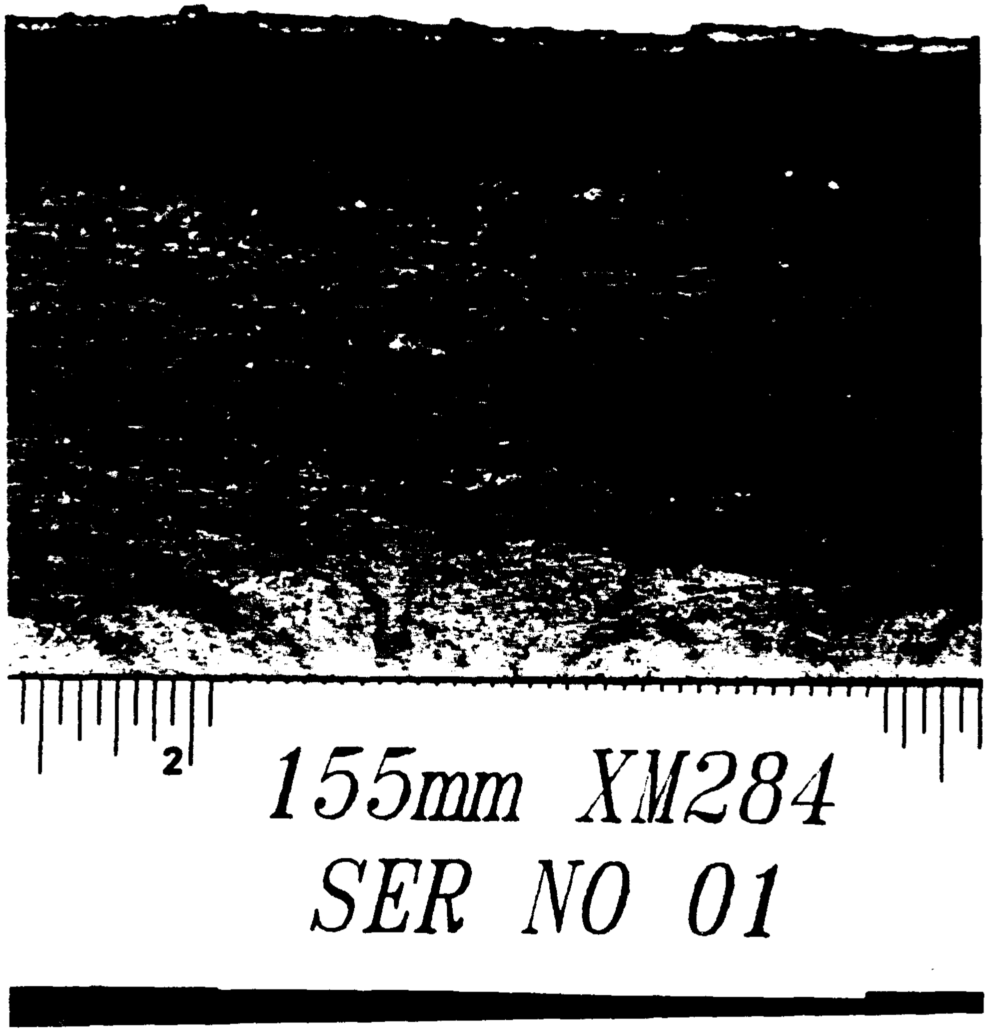

Figure 9. 155-mm XM284 Tube SN1 fracture surface.

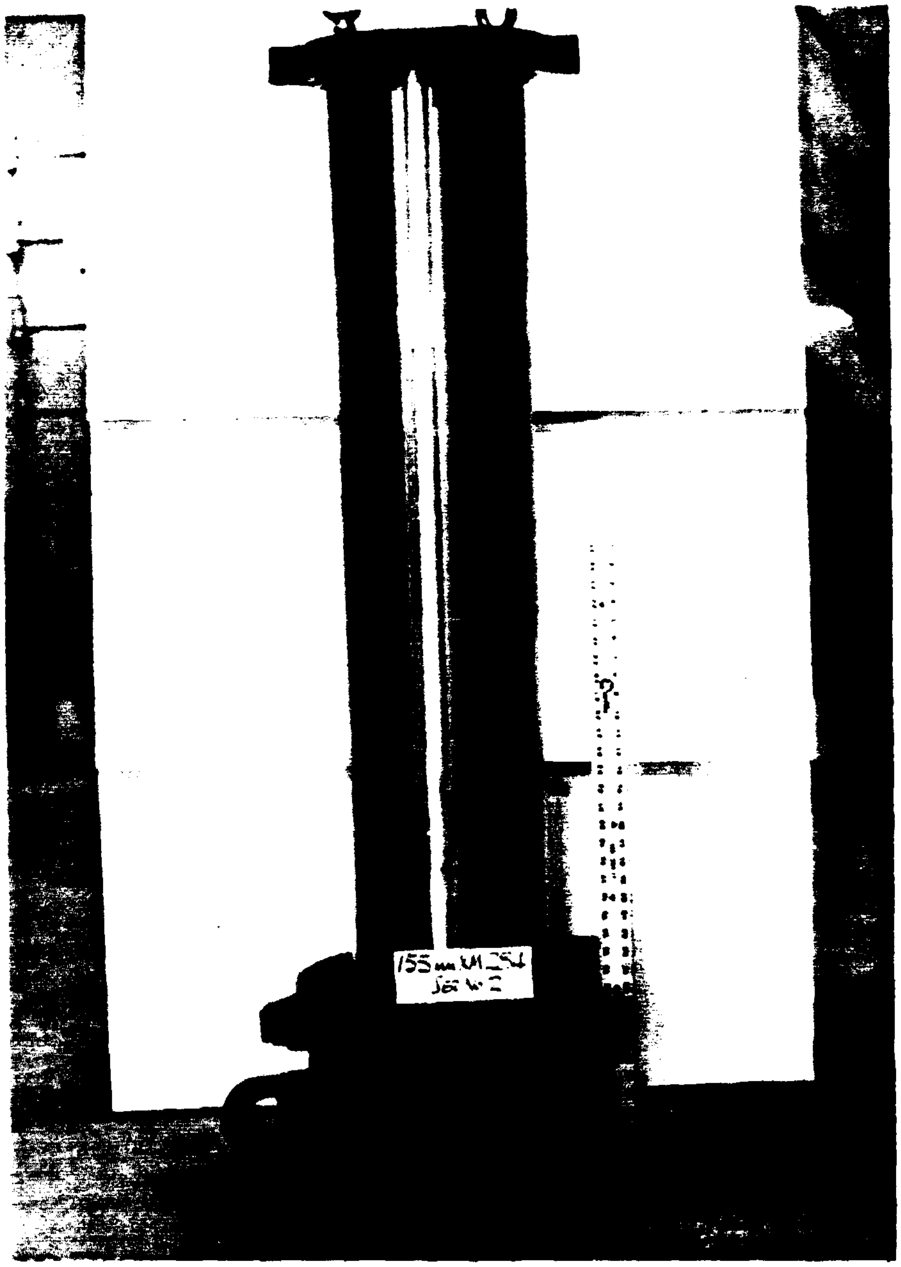

Figure 10. 155-mm XM284 Tube SN2 failure location.

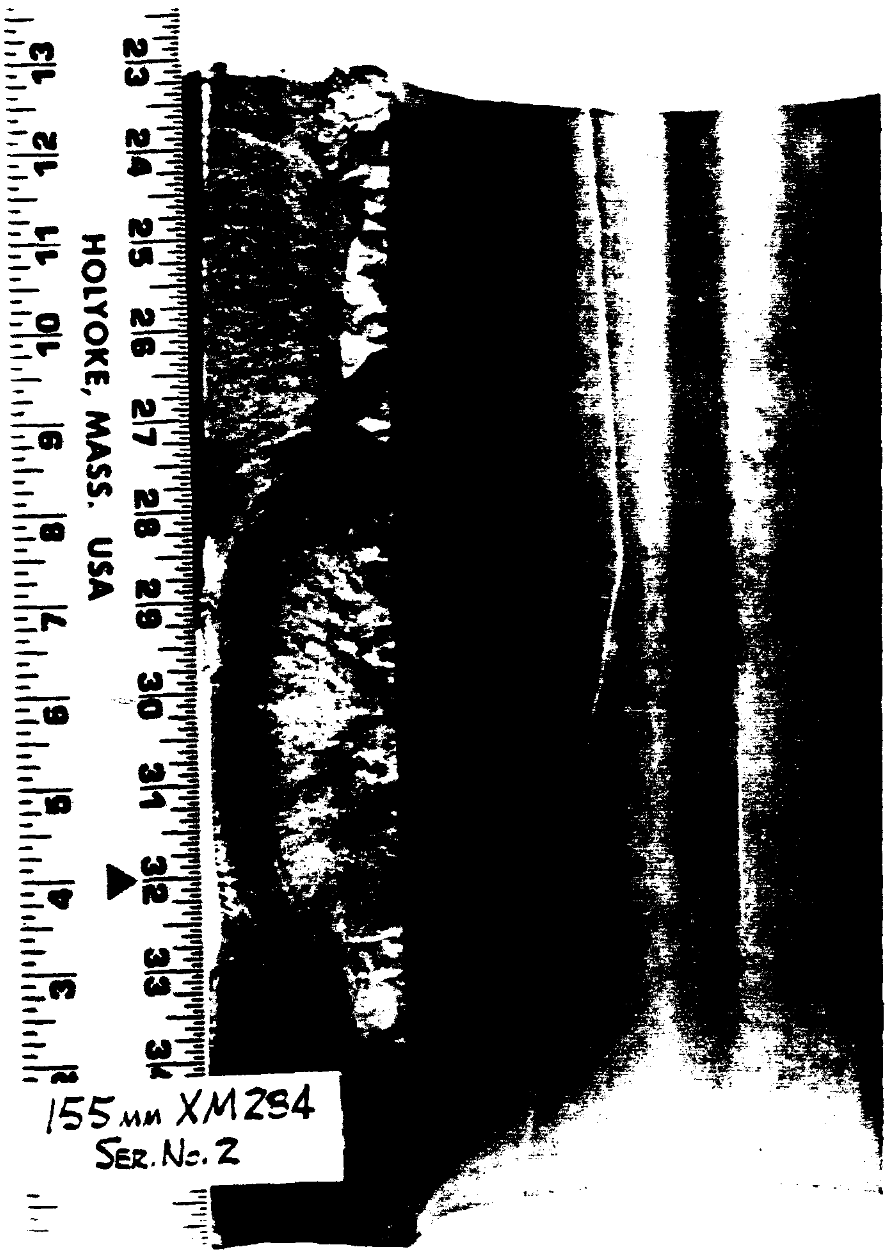

Figure 11. 155-mm XM284 Tube SN2 fracture surface.

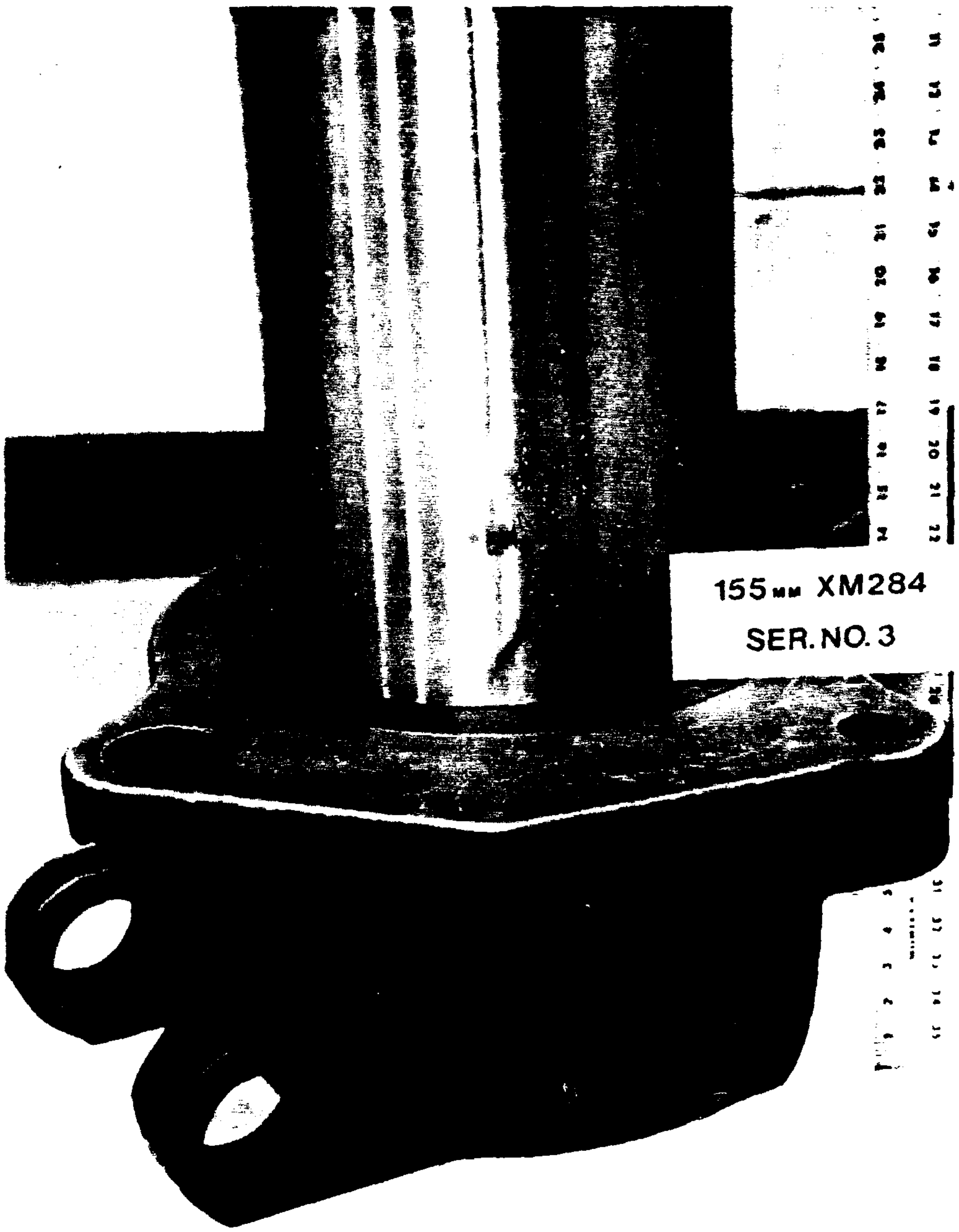

Figure 12. 155-mm XM284 Tube SN3 failure location.

Figure 13. 155-mm XM284 Tube SN3 fracture surface.

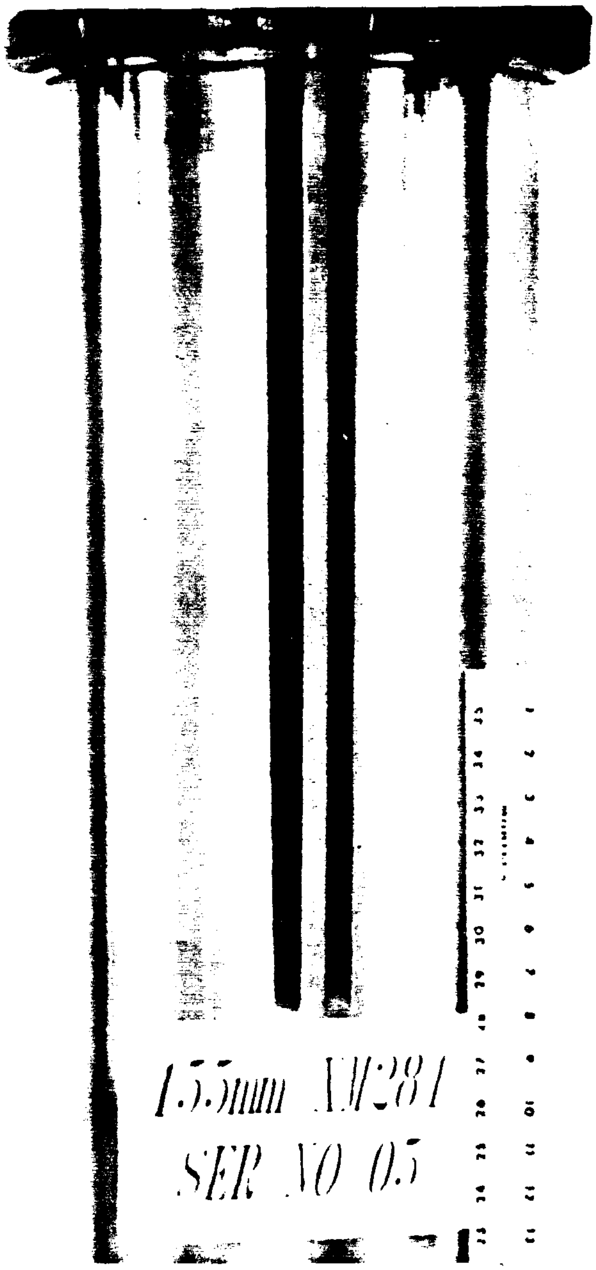

Figure 14. 155mm XM284 Tube SN5 failure location.

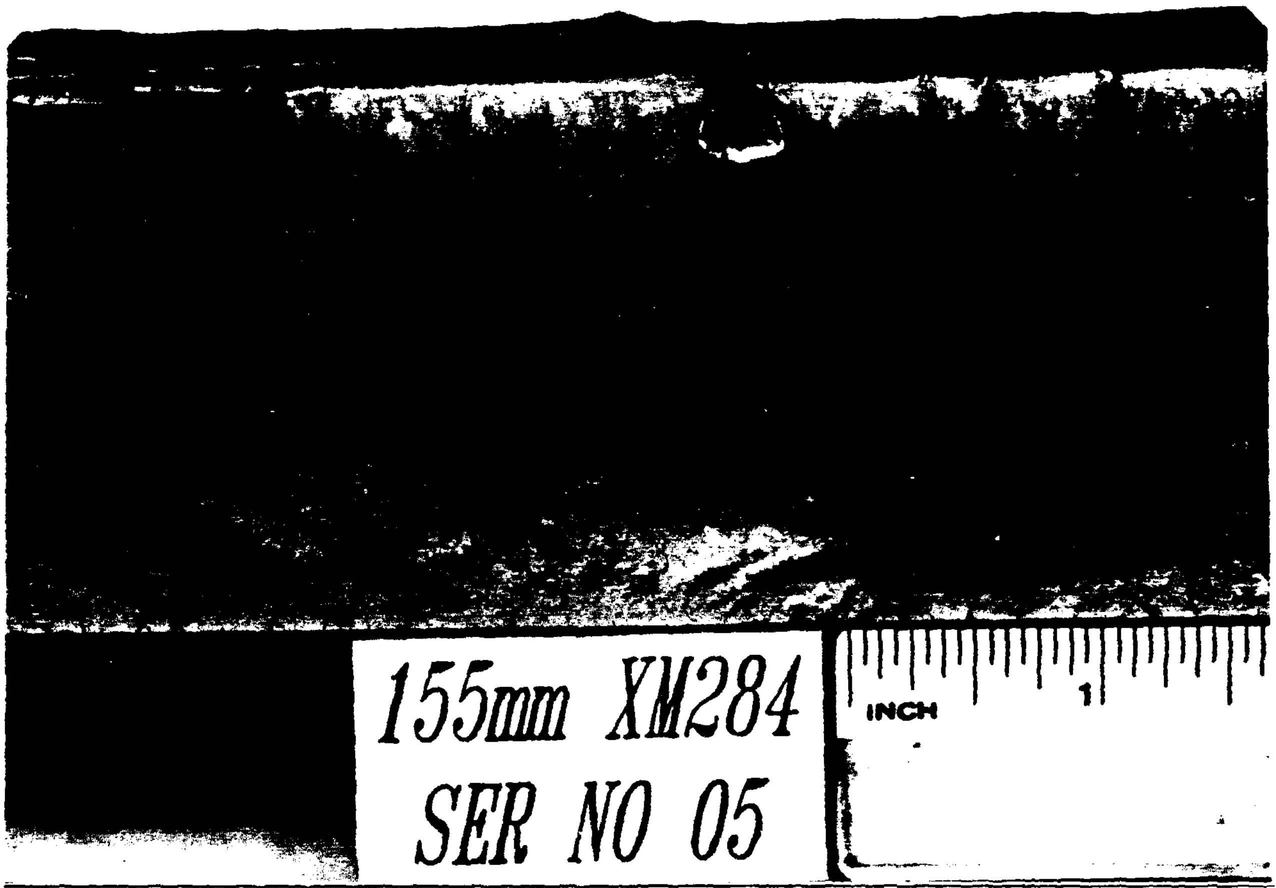

Figure 15. 155-mm XM284 Tube SN5 fracture surface.

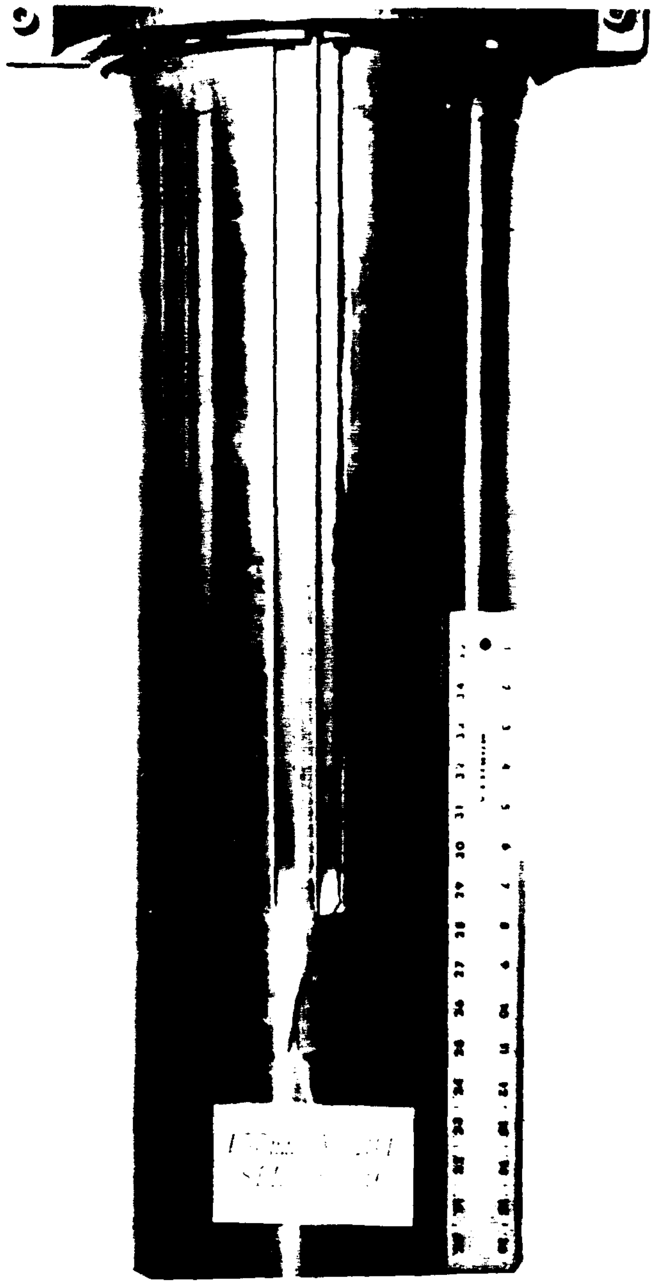

Figure 16. 155-mm XM284 Tube SN9 failure location.

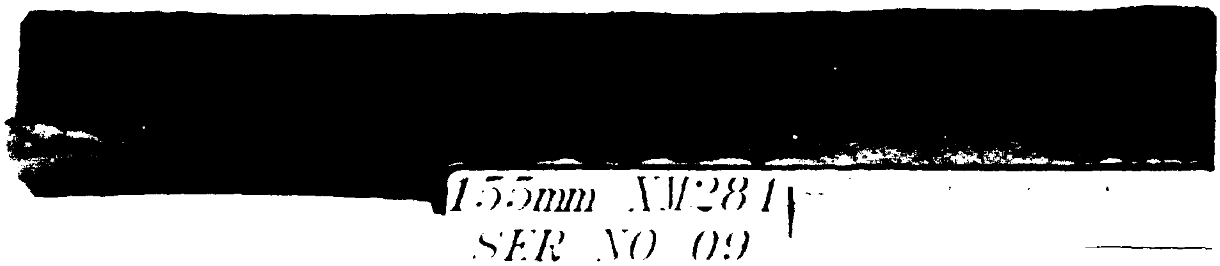

Figure 17. 155-mm XM284 Tube SN9 fracture surface.

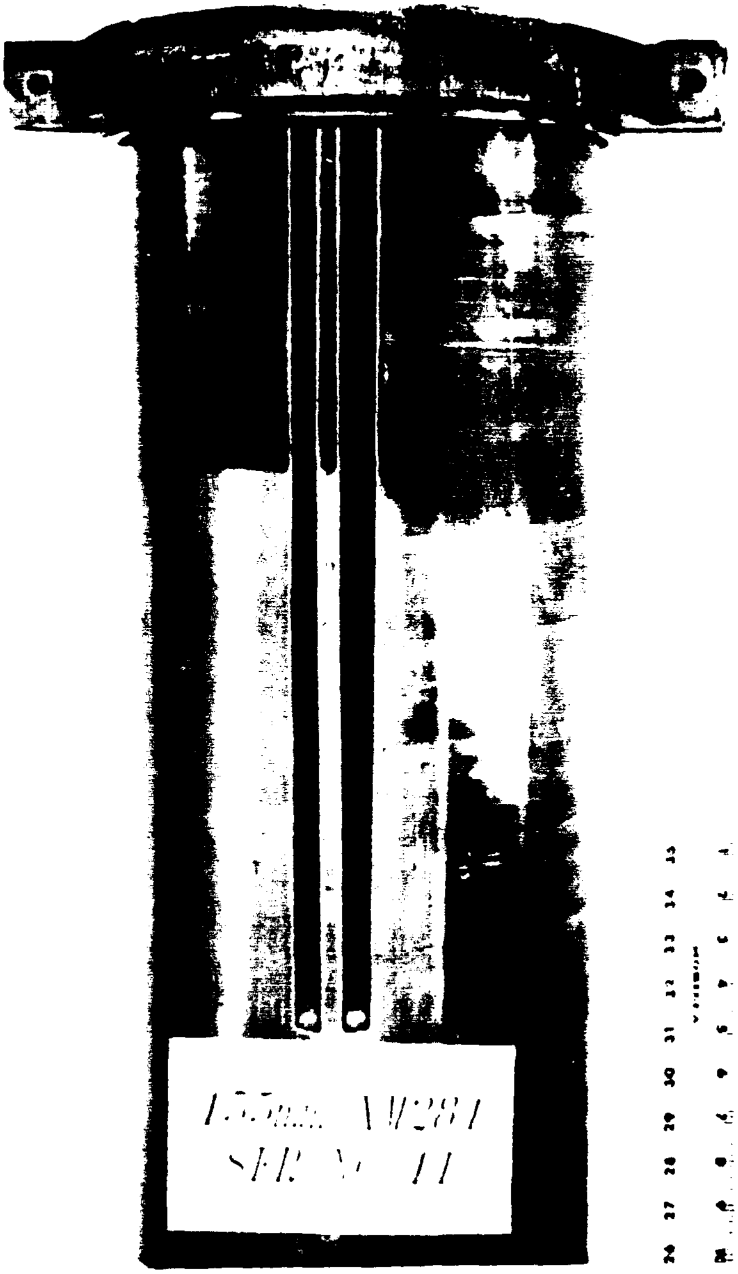

Figure 18. 155-mm XM284 Tube SN11 failure location.

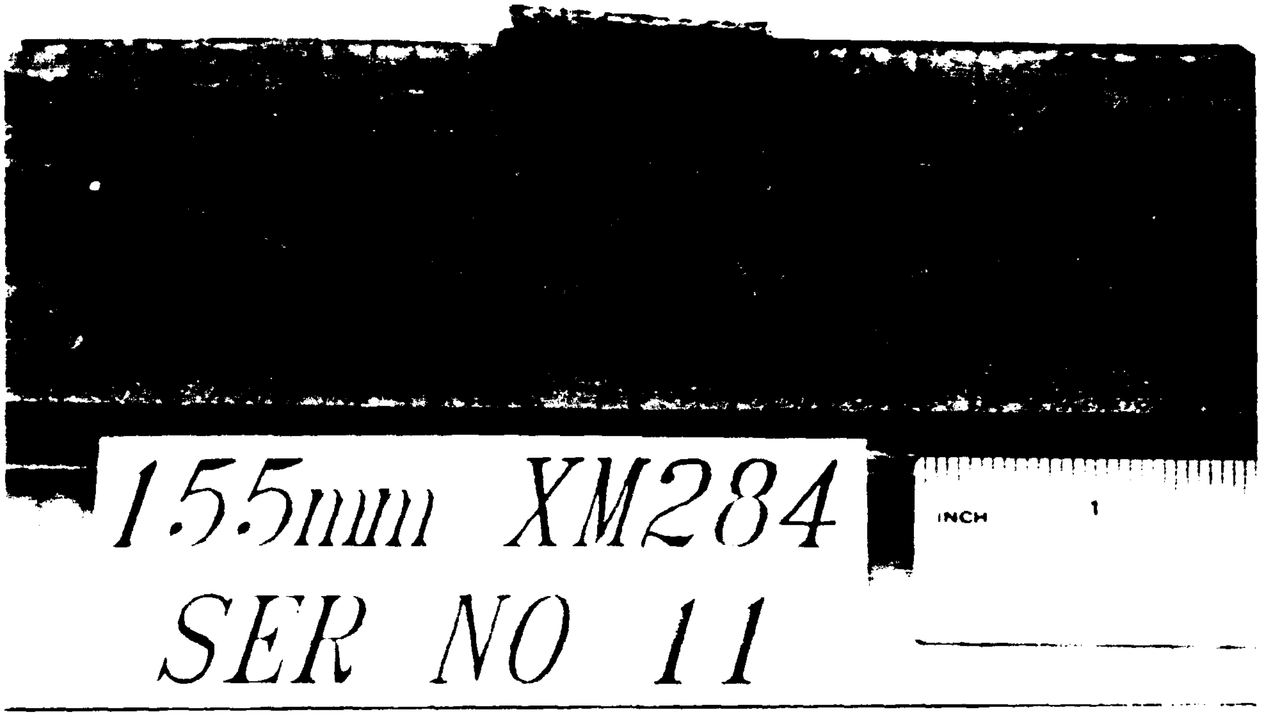

Figure 19. 155-mm XM284 Tube SN11 fracture surface.

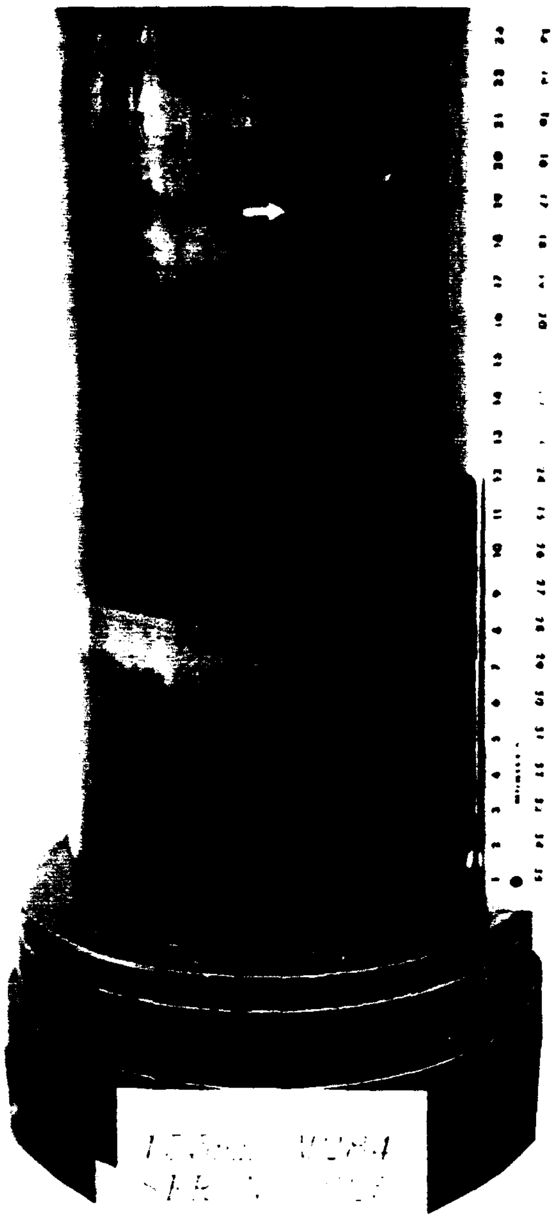

Figure 20. 155-mm M284 Tube SN825 failure location.

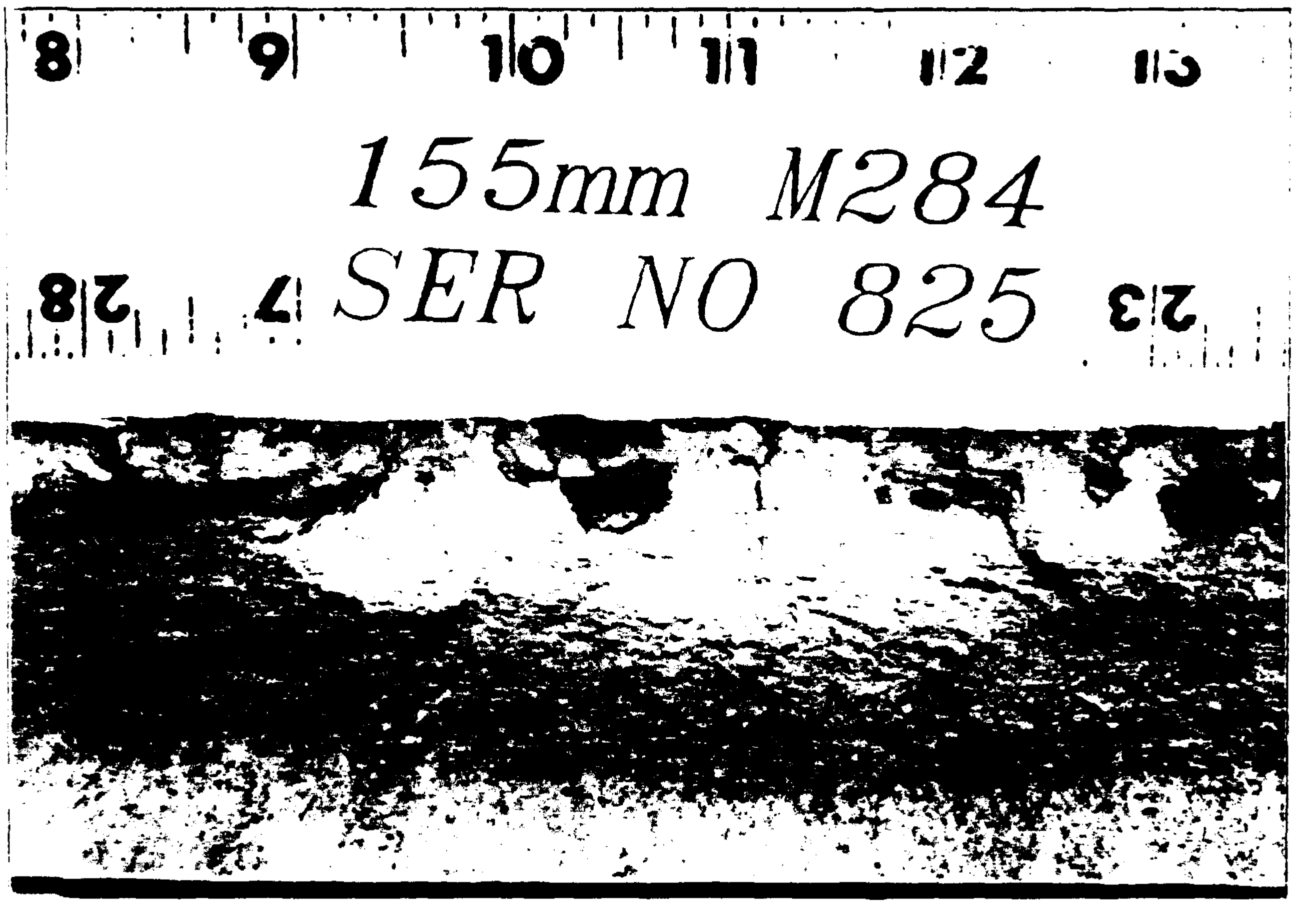

Figure 21. 155-mm M284 Tube SN825 fracture surface.

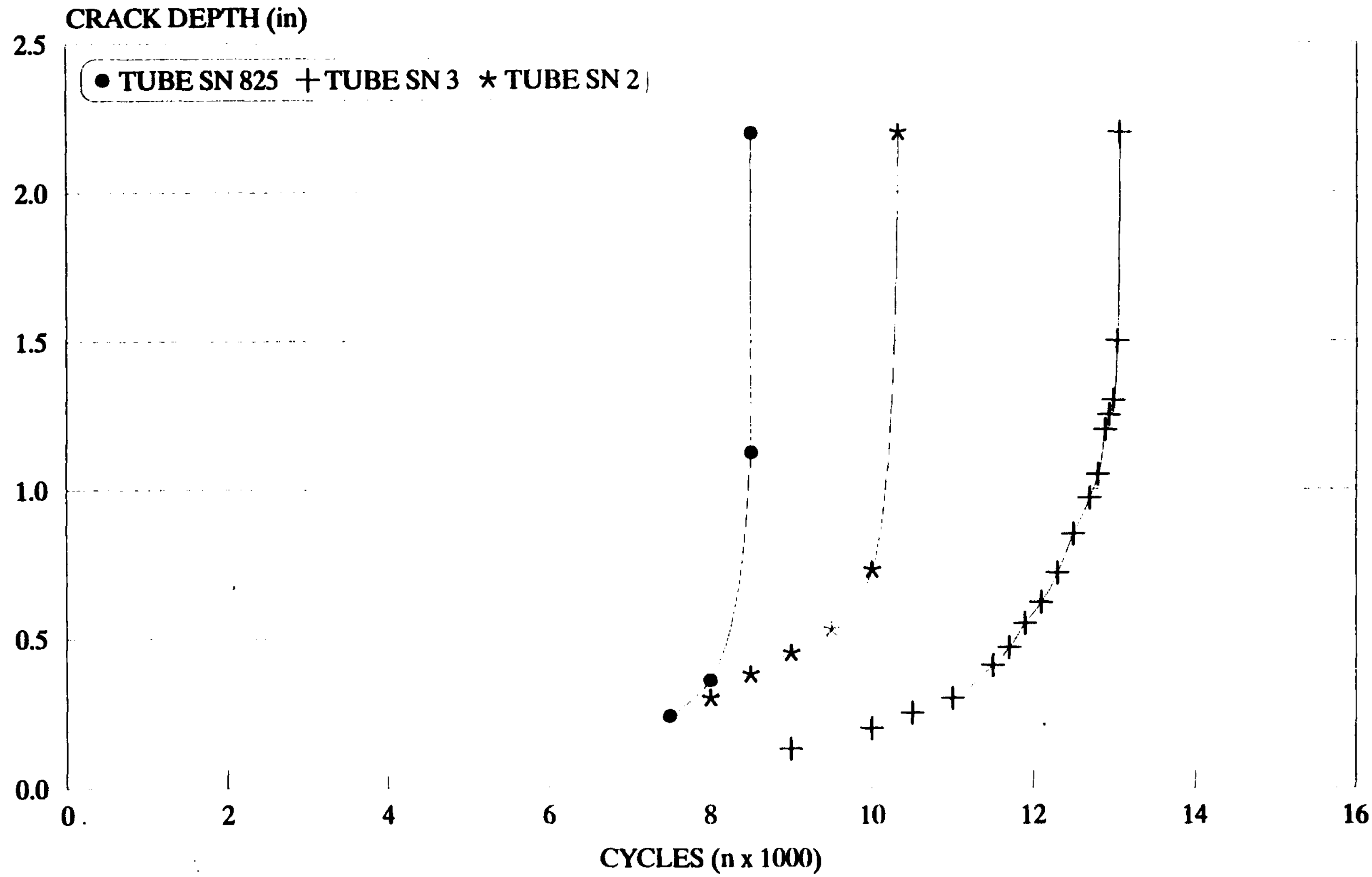

Figure 22. 155-mm M284 tube fatigue crack growth rates.

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